# Chapter 12
# Concrete Design

## 12-1. General

Most navigation dams are constructed as massive concrete structures (defined by American Concrete Institute Committee 207 as "any large volume of cast-in-place concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume changes to minimize cracking"). See EM 1110-2-2000 for a complete discussion of standard practice for concrete construction. There are three types of massive concrete structures commonly used for civil works projects: gravity structures, thick shell structures, and thick reinforced plates. Selection of concrete which meets design requirements is critical to long-term performance of these structures. The design requirements generally include the following characteristics:

*a. Strength.* Strength is an important characteristic of concrete. Typically, 3000-psi- or 4000-psi-strength concrete is utilized, but lower interior strengths or higher strengths may be used as well. Concrete strength may be varied by zones and may not always be limited to the normal 28-day designation. A 90- or 120-day strength, which is characteristic of concrete with a high percentage of pozzolan substitution for cement, may be utilized for long-term construction projects.

*b. Durability.* Concrete must resist deterioration by the environment to which it is exposed, including freezing and thawing, wetting and drying, chemicals, and abrasion.

*c. Placeability.* Placeability is described by the terms workability and consistency. These are affected by many factors, including water content, cement or pozzolan, and maximum size aggregate--the last of which, in turn, is influenced by the presence of steel reinforcement or embedded items.

*d. Economy.* The maximum economy can be achieved by minimizing the amount of cement utilized and, where appropriate, replacing portland cement with generally less expensive pozzolans. Economy is also improved by using the maximum size aggregate consistent with the dimensional requirements of the structures on the project, and by using aggregates available to the project.

*e. Ductility.* In areas of high seismic ground motions, the tensile strain capacity may be of great importance.

## 12-2. Nonlinear Incremental Structural Analyses

Determining the appropriate measures to cope with the problems associated with a massive concrete structure, including the division of the structure into separate elements such as piers, sills, or monoliths, is an important task. For major structures, a NISA should be used as a design for massive concrete structures if it will help achieve cost savings, develop more reliable designs for structures that have exhibited unsatisfactory behavior in the past, or predict behavior in structures for which a precedent has not been set. A NISA requires that a time-dependent heat transfer analysis be performed. The results of the heat transfer analysis are then used in a time-dependent stress analysis that simulates the incremental construction of the structure and uses nonlinear properties for modulus of elasticity, creep, and shrinkage. For more information on performing a NISA, refer to ETL 1110-2-324.

## 12-3. Parameters Affecting Cracking in Concrete

*a. General.* Cracking in non-massive reinforced concrete structures is primarily the result of tensile strains produced by loads applied to the structure. Steel reinforcement is provided to carry the tensile stresses. Cracking in mass concrete is primarily caused by restraint of volume change due to heat generation and subsequent cooling, autogenous shrinkage, creep/stress relaxation, or other mechanisms. Restraint limits the respective changes in dimensions and causes corresponding tensile, compressive, torsional, or flexural strains in the concrete. Of primary concern in mass concrete structures is restraint which causes tensile stresses and corresponding tensile strains. Restraint may be either external or internal. External restraint is caused by bond or frictional forces between the concrete and the foundation or underlying and adjacent lifts. The degree of external restraint depends on the relative stiffness and strength of the newly placed concrete and the restraining material and on the geometry of the section. Abrupt dimensional changes or openings in a monolith, such as wall offsets, gallery entrances and offsets, and reentrant corners, have caused external restraint that has resulted in cracking in concrete structures. Internal restraint is caused by temperature gradients within the concrete. The warmer concrete in the interior of the mass provides restraint as the concrete in the periphery of the mass cools at a different rate due to heat transfer to its surroundings. The degree of internal restraint depends upon the total quantity of heat generated, the severity of the thermal gradient, the thermal properties of the concrete, and thermal boundary conditions.

*b. Geometry.* The geometry of the structure is of course a major contributing factor to the behavior of the structure. Therefore, a NISA should not be performed until the structural geometry is at a stage where only minor changes to it are expected. While this parameter may be more difficult to alter than others, there may be instances in which a change is necessary. If such a change is made to the geometry of the structure, then coordination between all disciplines is necessary to ensure the change does not have an adverse effect on some other function of the structure. A change in the geometry will generally require some type of revision to the model's mesh.

*c. Reinforcing.* Reinforcing is an integral part of non-massive concrete structures and of many of the massive concrete structures used within the Corps of Engineers. Reinforcement for all non-massive concrete structures should be designed in accordance with EM 1110-2-2104. See EM 1110-2-2000 for a comprehensive discussion of standard practice for concrete construction. For large wall and floor sections, reinforcement spacing should generally be set at 12 in. for ease of construction. In non-massive concrete sections, temperature and shrinkage reinforcement is required to control cracking. Generally, small bars at close spacing provide the best control. However, for walls 2 ft thick or more, number 9 bars at 12-in. spacings are commonly used to ease construction while still providing the required steel percentage. In gravity walls, however, the requirements of EM 1110-2-2104 regarding the minimum steel do not apply. To date there has been limited use or recognition of reinforcing in NISA analyses, due to the fact that many of the structures analyzed had no cracking problems, and adding reinforcing in the model when cracking is not occurring has little effect on results. If an analysis predicts cracking in a structure and measures to eliminate the cracking are unsuccessful, then reinforcement should be included in the model. Resulting stresses in the reinforcing bars should be monitored, reported, and compared to the yield strength of the reinforcing. If cracking is occurring in a location of minimal reinforcing or at corners of openings, increasing the amount of steel transverse to the crack can help control or arrest the crack. Typically, reinforcing steel placed at 45 deg at corners is very effective at arresting corner cracking. Special attention must be paid to providing proper concrete cover for all reinforcing bars (see EM 1110-2-2104).

*d. Seismic.* Reinforcing steel must be properly contained to ensure good performance during an earthquake. See ETL 1110-2-365 for further guidance.

*e. Material parameters.*

(1) A number of material parameters can be controlled to limit cracking related to restrained volume change. They include heat generation of the concrete; mechanical properties of the concrete, including compressive and tensile strength, tensile strain capacity, modulus of elasticity, linear coefficient of thermal expansion, creep/stress relaxation, and autogenous shrinkage; and thermal properties of the concrete, including specific heat and thermal conductivity.

(2) These properties are governed by the selection of materials used to make the concrete, including cementitious materials (portland cement, ground granulated iron, blast furnace slag, and pozzolans such as fly ash), aggregates, chemical admixtures, etc.; and by the proportions of these materials in the concrete mixture. Many of these properties are also dependent on the maturity of the concrete and are thus time and temperature dependent. Close scrutiny of the selection of concrete mixture materials and proportions should be part of a properly conducted concrete materials study. Due consideration should be given to the performance and economy of the selected mixture. The study should be conducted according to the guidance in EM 1110-2-2000 and documented in a concrete materials design memorandum.

*f. Construction procedures.* A number of construction parameters can be controlled to limit cracking due to restrained volume change. They include lift height, time between placement of lifts, concrete placement temperature, curing method, use of insulation, monolith geometry including section thickness, monolith length, and location and size of inclusions such as galleries. In addition, the time of year a monolith is constructed can be controlled if it has been determined by the NISA that a particular start date is beneficial. Any construction requirements or restrictions identified by the NISA must be clearly stated in the construction contract documents.

*g. Vertical construction joints within a monolith.* There may be some projects for which vertical construction joints become necessary due to excessively large concrete placements. If this is the case, lift sequences creating vertical joints should be accounted for in the incremental construction analysis procedure. Stresses across a vertical construction joint should be examined closely for determination of any special measures needed in the design and construction of the joint (e.g., placement of reinforcement bars across the joint face). In addition, a 3-D analysis should be considered for monoliths with vertical construction joints to confirm results obtained in the 2-D analysis, because the joints themselves will be located in the out-of-plane direction.

## 12-4. Concrete Quality for Dam Spillway and Stilling Basin

*a. Spillway function and composition.* The primary function of a navigation dam concrete spillway is to provide a controlled release of surplus water from the impounded pool so that the water level can be regulated for navigation traffic use. The spillway may be composed of the following features: ogee spillway crest and shape, stilling basins, apron, bucket, end sill, and baffle blocks, as well as spray walls, separation walls, and training walls.

*b. Concrete durability.* The concrete for all the above features must be able to resist the effects of environmental deterioration, including freezing and thawing, wetting and drying, chemicals, and abrasion. In addition, the concrete should be able to resist damage caused by waterborne rocks and gravel, floating ice, floating tree trunks, and debris of all kinds in the high-velocity flowing water. Damage to the concrete in spillways and stilling basins is a constant maintenance problem on many existing Corps projects. On various projects, abrasion-erosion has ranged from a few inches to several feet, and, in some cases, severe damage has occurred after only a few years of operation. The fact that many spillways cannot be easily or economically unwatered for inspection and repair makes the initial quality and the placement of the concrete all the more important. To protect the spillway concrete from all the potentially damaging elements, durable concrete mixes and proper concrete placement requirements should be provided in accordance with all the recommendations outlined in EM 1110-2-2000. Special attention must also be given to providing proper concrete cover over steel reinforcement (see EM 1110-2-2104).

## 12-5. Second Placement Concrete

*a. Purpose.* Second placement concrete is necessary for a dam structure at locations where precise settings are required for alignment and/or elevations for embedded steel items. These items and locations may include horizontal seal plates on spillway crests for spillway gates, vertical side sealing and rubbing plates for "J" seals attached to spillway gates, machinery bases for support of gate operating machinery, horizontal seal plates for spillway bulkheads, vertical plates for vertical-lift gates and spillway bulkheads to bear on and roll on, corner protection for spillway bulkhead slots (upstream and downstream), dogging devices for spillway bulkheads, and crane rails for a movable crane located on the service bridge.

*b. Design consideration.* These second placement blockouts require careful sizing and detailing so that enough space is available for adjusting the steel items to line and grade and to allow for placing and vibrating concrete. The following items also require special attention: the concrete mix (which must be designed with the proper aggregate size to allow good placement); the concrete mix design (which must provide for minimum shrinkage); reinforcing steel extending from the mass concrete placement; additional steel for the second placement; and embedded bolts and adjustment provisions for securing the steel items in position. For typical second placement details, see Plate 19. EM 1110-2-2000 contains guidance in proportioning and constructing blackout concrete.